Home Search Collections Journals About Contact us My IOPscience

Afforestation to mitigate climate change: impacts on food prices under consideration of albedo

effects

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2016 Environ. Res. Lett. 11 085001

(http://iopscience.iop.org/1748-9326/11/8/085001)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 84.168.93.96 This content was downloaded on 28/12/2016 at 07:36

Please note that terms and conditions apply.

You may also be interested in:

Investigating afforestation and bioenergy CCS as climate change mitigation strategies Florian Humpenöder, Alexander Popp, Jan Philip Dietrich et al.

The global economic long-term potential of modern biomass in a climate-constrained world David Klein, Florian Humpenöder, Nico Bauer et al.

Impacts devalue the potential of large-scale terrestrial CO2 removal through biomass plantations L R Boysen, W Lucht, D Gerten et al.

<u>Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS)</u> Matteo Muratori, Katherine Calvin, Marshall Wise et al.

Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture Isabelle Weindl, Hermann Lotze-Campen, Alexander Popp et al.

The economic potential of bioenergy for climate change mitigation with special attentiongiven to implications for the land system Alexander Popp, Jan Philipp Dietrich, Hermann Lotze-Campen et al.

Drivers and patterns of land biosphere carbon balance reversal Christoph Müller, Elke Stehfest, Jelle G van Minnen et al.

Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios

Keith Wiebe, Hermann Lotze-Campen, Ronald Sands et al.

Environmental Research Letters

LETTER

2

OPEN ACCESS

CrossMark

RECEIVED 27 December 2015

REVISED 27 June 2016

ACCEPTED FOR PUBLICATION 11 July 2016

PUBLISHED 27 July 2016

licence

Original content from this work may be used under the terms of the Creative Commons Attribution 3.0

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOL



Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects

Ulrich Kreidenweis^{1,2}, Florian Humpenöder¹, Miodrag Stevanović¹, Benjamin Leon Bodirsky^{1,3}, Elmar Kriegler¹, Hermann Lotze-Campen^{1,4} and Alexander Popp¹

¹ Potsdam Institute for Climate Impact Research, Potsdam, Germany

University of Hamburg, Center for Earth System Research and Sustainability, Hamburg, Germany

Commonwealth Scientific and Industrial Research Organisation, St. Lucia, Australia

Humboldt University of Berlin, Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Berlin, Germany

E-mail: kreidenweis@pik-potsdam.de

Keywords: climate engineering, carbon dioxide removal, afforestation, food prices, albedo Supplementary material for this article is available online

Abstract

Ambitious climate targets, such as the 2 °C target, are likely to require the removal of carbon dioxide from the atmosphere. Afforestation is one such mitigation option but could, through the competition for land, also lead to food prices hikes. In addition, afforestation often decreases land-surface albedo and the amount of short-wave radiation reflected back to space, which results in a warming effect. In particular in the boreal zone, such biophysical warming effects following from afforestation are estimated to offset the cooling effect from carbon sequestration. We assessed the food price response of afforestation, and considered the albedo effect with scenarios in which afforestation was restricted to certain latitudinal zones. In our study, afforestation was incentivized by a globally uniform reward for carbon uptake in the terrestrial biosphere. This resulted in large-scale afforestation (2580 Mha globally) and substantial carbon sequestration (860 GtCO_2) up to the end of the century. However, it was also associated with an increase in food prices of about 80% by 2050 and a more than fourfold increase by 2100. When afforestation was restricted to the tropics the food price response was substantially reduced, while still almost 60% cumulative carbon sequestration was achieved. In the medium term, the increase in prices was then lower than the increase in income underlying our scenario projections. Moreover, our results indicate that more liberalised trade in agricultural commodities could buffer the food price increases following from afforestation in tropical regions.

Introduction

To achieve ambitious climate targets, such as limiting global mean temperature increase to below 2 °C compared to preindustrial levels, a strong decline in global greenhouse gas (GHG) emissions is urgently needed (Clarke *et al* 2014). Yet simply reducing GHG emissions might not be sufficient, or might only be achievable at high cost, so that carbon dioxide removal from the atmosphere (CDR) could become necessary in the second half of the century. Accordingly, most scenarios of the fifth assessment report of the IPCC (AR5) that are consistent with the 2 °C target include negative net CO₂ emissions (Clarke *et al* 2014, Fuss *et al* 2014). This is also acknowledged in the recent Paris Agreement of the UNFCCC, in which parties

© 2016 IOP Publishing Ltd

agreed to aim for a balance between anthropogenic emissions and sinks of GHGs in the second half of the century (UNFCCC 2015). Land-based mitigation strategies such as afforestation and avoided deforestation could make important contributions to achieving this target (Smith *et al* 2014).

Afforestation offers a high carbon sequestration potential at moderate cost, and could therefore become an alternative to or could complement other mitigation options. Cost estimates for afforestation are lower than for other carbon removal technologies such as bioenergy with carbon capture and storage (BECCS) and by an order of magnitude lower than for direct air capture (Smith *et al* 2015). Strengers *et al* (2008) calculated supply curves of afforestation on abandoned agricultural land and found that in 2075 more than 50% of the overall potential could be supplied at costs of less than 200 \$/tC, which is relatively cheap compared to other mitigation options. Edmonds et al (2013) showed that a 2 °C warming at the end of the century would be possible without BECCS, but would require substantial carbon sequestration through afforestation, especially if mitigation action is delayed in some countries. Calvin et al (2014) illustrated that afforestation is an economically attractive option. When in their study a carbon tax consistent with limiting radiative forcing to $3.7 \,\mathrm{W}\,\mathrm{m}^{-2}$ was applied to the energy and land-use system, global forest area increased by about 20%. Humpenöder et al (2014) found that a reward for terrestrial carbon uptake could provide an incentive for large-scale afforestation, resulting in cumulative removal of more than 700 Gt CO₂ by 2095. With such a huge potential, afforestation could play a considerable part in climate change mitigation efforts.

On the downside, large-scale afforestation might lead to a considerable increase in food prices through increasing competition for land between forest and agricultural production. Similar concerns have been raised in the past with regard to first-generation biofuel production, but the demand for biofuel was only one factor of many that contributed to food price hikes in recent years and its contribution was estimated to be rather modest (Mueller et al 2011, Persson 2015). Similarly, a model intercomparison study showed that second-generation bioenergy production consistent with the 2 °C target could result in rather moderate food price increases up to 2050 if the land available for the expansion of agriculture were not restricted and if necessary investments into technology and development (R&D) were anticipated (Lotze-Campen et al 2014). Afforestation, however, may need substantially more area to achieve a similar level of carbon dioxide removal to BECCS (Humpenöder et al 2014), and could therefore have a much stronger influence on land-use competition. Bioenergy crops are harvested regularly, while once established, forests need to be maintained also under declining carbon accumulation rates if the carbon is to remain stored. Wise et al (2009) found that a carbon tax on terrestrial and industrial emissions could lead to an expansion of managed forests but also to a more than doubling of corn prices. In a study by Reilly et al (2012) a price on land carbon emissions created an incentive to reforest but also increased food prices. Calvin et al (2014) assessed the effect of afforestation with the integrated assessment model GCAM and found that wheat prices increased to 320% in 2095 compared to 2005 values.

The effectiveness of afforestation for climate mitigation differs depending on the location, making its application unfavourable in some regions. This is because establishing forests leads to two effects that often have an opposing influence on the average global temperature. On the one hand, while growing, trees take up carbon from the atmosphere and store it in



their biomass (biogeochemical effect). On the other hand, changing land-cover to trees also affects the amount of short-wave radiation reflected back to space (biogeophysical effect), directly by surface albedo and indirectly by the contribution to cloud formation. This biogeophysical effect varies as a function of latitude (Bonan 2008). Several studies with earth system models have shown that an expansion of forest in the tropics results in cooling, while afforestation in the boreal zone might have only a limited effect or might even result in global warming (Bala et al 2007, Bathiany et al 2010, Arora and Montenegro 2011). Bright (2015) and Bright et al (2015) provide a good overview over the biogeochemical and biophysical processes that affect global and local temperatures as a consequence of land-cover and management change.

In the study presented here, we assessed global and regional food price impacts of large-scale afforestation with the Model of Agricultural Production and its Impacts on the Environment (MAgPIE). Earlier studies, using similar methods, have assessed bioenergy potentials (van Vuuren et al 2009, Erb et al 2012), requirements for and consequences of forest and biodiversity protection (Kraxner et al 2013, Overmars et al 2014, Erb et al 2016) or estimated climate change impacts on food prices (Delincé et al 2015). Five scenarios were analysed, one in which a CO₂ price on land-use-change emissions avoids deforestation and three where the CO₂ price created an additional incentive for afforestation. In these cases afforestation was either unrestricted, prevented in the boreal zone, or limited to the tropical zone. These scenarios were compared to a business-as-usual case without emission pricing. As afforestation was expected to increase food prices, we furthermore assessed whether more liberalised trade conditions could have an alleviating effect on food prices.

Methods

The land-use model MAgPIE

Future land-use, carbon sequestration and food price development as affected by afforestation were modelled with the partial equilibrium model MAgPIE (Lotze-Campen *et al* 2008, Humpenöder *et al* 2014, 2015, Popp *et al* 2014). MAgPIE is an agro-economic land-use model that minimises the global costs of agricultural production for a given agricultural demand under a set of economic and biophysical constraints. By this it computes optimal, spatially explicit future land-use patterns in five-year time steps.

Agricultural demand in the model is based on projections of future population and gross domestic product (GDP) of the SSP2 scenario (KC and Lutz 2014, Dellink *et al* 2015, O'Neill *et al* 2015). This scenario assumes that global population peaks in 2070 at 9.4 billion people, while per capita GDP continues to increase until 2100. Future demand for calories and livestock share in consumption are derived through a regression model that has been estimated with historical data for calories consumed and GDP development (Bodirsky *et al* 2015) (see also figures S2 and S3). Feed demand for livestock production results from animalspecific feed baskets (Weindl *et al* 2010, 2015). Socioeconomic parameters, such as the demand, are exogenously fed into the model at the level of ten geo-economic world regions.

The model considers the production of 17 different crop groups and 5 livestock commodities. Bioenergy production was not included in this study. Potential crop yields, carbon densities and water availabilities are derived by the Dynamic Global Vegetation Model LPJmL (Bondeau *et al* 2007, Fader *et al* 2010, Waha *et al* 2012, Müller and Robertson 2014) on a spatial resolution of 0.5°. For the starting year of the model (1995) crop yields were calibrated to match attained country yield levels and regional production areas reported by FAOSTAT. For an efficient, nonlinear modelling under computational constraints, spatial input data were aggregated to 600 clusters with similar crop yields, hydrological conditions and market access (Dietrich *et al* 2013).

In the model there are several options to respond to future changes in demand or other pressures on the land-use system, such as afforestation. The land-use pattern can react flexibly so that one land-use class can be extended at the expense of others, e.g. cropland can be expanded onto former pasture areas, or afforestation might take place on present-day croplands. The model can also reallocate production to locations that are more productive, domestically within a region or via international trade. Another option implemented is the use of irrigation. Finally, agricultural production can be intensified by endogenous investment decisions in yield-increasing technological change.

Agricultural production and all options to increase production are associated with costs. Factor costs account for costs related to capital, labour and fertilizer use and were derived from the GTAP database (Narayanan and Walmsley 2008). The change from one land-use class to another is subject to regionally differing land conversion costs (Schmitz 2012). Yield increases induced by technological change are endogenous in MAgPIE and are connected to additional investment costs for Research & Development (R&D). These costs were derived through a regression between historical investments and observed yield increases (Dietrich et al 2014). An investment horizon of 30 years and a discount rate of 7% are assumed for all investment decisions. Starting from the present distribution of areas equipped for irrigation (Siebert et al 2007), the model can increase irrigated areas at investment costs for the creation of the infrastructure and costs for operation and maintenance (Bonsch et al 2016). The cost effectiveness of production is also influenced by intraregional transport costs which



make production at locations far from markets more expensive.

Food commodities can be traded between the world regions. Two trade pools are implemented in the model. Within the first trade pool, trade flows are fixed to fulfil regional, historically observed self-sufficiency rates calculated from FAOSTAT (2010). For the following time steps, the influence of this first trade pool is reduced depending on the scenario, and food commodities are to a larger share traded according to regional comparative advantages (Schmitz *et al* 2012) (figure S4).

Afforestation and avoided deforestation are incentivized by a price on CO₂ emissions from the land system. While the CO₂ price renders deforestation and the conversion of pasture to cropland more costly, carbon dioxide removal through afforestation is rewarded and lowers the costs in the objective function of the model. Afforestation is implemented as induced regrowth of natural vegetation. Carbon accumulation in living biomass follows sigmoidal tree growth curves where the upper limit is defined by carbon densities from the LPJmL model. Soil and litter carbon densities are assumed to increase linearly over 20 years, starting from the weighted average carbon density of cropland and pasture (Humpenöder et al 2014, 2015). For this study we assumed a CO₂ price that starts at 30 US\$ per tonne of CO₂ in 2020 and increases by 5% each year (similar to Calvin et al 2012 and Kriegler et al 2013).

Scenarios

Afforestation is considered to be most effective in the tropical zone because the combined effect of carbon sequestration and albedo change are assumed to lead to a net cooling, while for the boreal and temperate zones the effect is presumably much lower. To assess the food price effects of afforestation under differing levels of ability to decrease global temperatures, we considered three scenarios where afforestation was limited to certain latitudinal zones. Within these areas the decision to afforest was based on its cost-effectiveness under a CO₂ price on land-use emissions. The effect of albedo was not included directly in the model, but scenarios with different influence on albedoinduced radiative forcing were assessed. In the first scenario afforestation was not restricted at all (unrestricted aff), in the second not allowed in the boreal zone north of 50°N (no boreal aff), and finally it was limited to the tropical zone between 20°S and 20°N (only tropical aff). The definition of tropical and boreal zones thereby follows Bala et al (2007). These afforestation scenarios were compared to a scenario of avoided deforestation, where terrestrial CO₂ emissions were also priced but no afforestation was considered, and to a business as usual (BAU) case without any emissions pricing (see also table 1).

While limiting large-scale afforestation to the tropics seems plausible from a climate mitigation



Table 1. Scenario description and resulting afforested area, cumulative land-use emissions, food prices indices and technological change rates. Reference year for the figures is 2010.

Scenario	Afforestation	CO ₂ price	Afforested area (Mha)		Cumulative emissions (Gt CO ₂)		Food price index (2010 = 100)		Average annual yield-increasing technological change rate	
			2050	2100	2050	2100	2050	2100	2050	2100
BAU	No	No	0	0	88	91	103	92	0.76%	0.44%
Avoided defor	No	Yes	0	0	8	2	128	95	1.09%	0.61%
Unrestricted aff	Allowed globally	Yes	1614	2577	-356	-860	186	442	1.66%	1.34%
No boreal aff	Allowed < 50°N	Yes	1351	2240	-330	-791	180	402	1.60%	1.29%
Only tropical aff	Allowed 20°S–20°N	Yes	921	1235	-266	-525	152	138	1.38%	0.81%

perspective, it could still result in severe food price hikes in tropical regions. Enhanced international trade of agricultural commodities could be one option to buffer these price increases in tropical regions. For the *only tropical aff* case we therefore assessed how more liberalised trade influenced food prices (*only tropical aff tradelib*). In this scenario, trade departed more quickly from historical agricultural trade patterns towards more international trade based on comparative advantages. While in our default setting the influence of historical trade patterns decreased by 0.5% per year, in this scenario it was reduced by 1% per year (see also figure S4).

For these scenarios we calculated Laspeyres food price indices that comprise vegetable and livestock products. The Laspeyres formula weights prices according to base year quantities and is also the common approach used, for instance, by The World Bank (2015) to calculate its consumer price index. Food prices derived from MAgPIE reflect the marginal costs of food production (shadow prices), i.e. the costs that would arise for the production of one additional commodity unit. They are formed as a consequence of altered demand and production costs and therefore show the relative long-term commodity price development. Food prices in the BAU scenario are driven by the increasing demand for food from a growing and wealthier population. In the avoided deforestation scenario food prices additionally reflect the pricing of land-use-change emissions, the thus reduced attractiveness to reduce the area of forest or convert pastures to cropland, and the increased need to invest into yield-increasing technology. Food prices in the afforestation scenarios are the result of all these factors and an additional reward on carbon uptake through afforestation which leads to decreasing agricultural areas.

Results

Land demand and required technological change

The growing demand for food (figure S2) leads to an expansion of croplands in the *BAU* scenario. Globally, cropland area increases by 360 million hectares (Mha) until 2100, leading to a reduction of the area of pasture

by 275 Mha and of forests and other natural vegetation by about 85 Mha. The introduction of a price on CO₂ emissions from land-use change stops the net conversion of forest to agricultural areas on a global level. In the *avoided deforestation* scenario, cropland expands by 77 Mha, with most of the change happening in Africa (40 Mha) at the expense of pasture (17 Mha) and forest (13 Mha), while in Europe there is some regrowth of forests (14 Mha).

In the afforestation scenarios the CO_2 price provides an incentive for afforestation so that forest area increases substantially in all regions where this option was given considering the latitudinal restrictions. Under *unrestricted* afforestation, more than 2500 million ha are newly afforested globally between 2010 and 2100, which is equivalent to an increase of global forest area by more than 60%. The largest areas of afforestation in absolute terms are in Africa (630 Mha) and Latin America (600 Mha), but afforestation is also substantial in all other regions when compared to their total land areas (figure 1). While in most regions afforestation leads mainly to a reduction in pasture, in Europe and Pacific Asia more croplands are converted to grow forests.

The restriction to *no boreal* afforestation reduces the afforested area by about 13% globally, but hardly changes the amount of land conversion in tropical regions. In the *only tropical* afforestation scenario, in contrast, the area of forest establishment is cut by half (table 1). While it remains at comparable levels in the tropical regions Africa and Pacific Asia it is lower in Latin America (435 Mha), because areas in the south (>20°S) were not considered for afforestation (figure S9).

While in the *BAU* scenario investments into yieldincreasing R&D are rather modest, the introduction of a price on CO_2 emissions prevents further agricultural expansion and necessitates higher yields in the *avoided deforestation* scenario. In the afforestation scenarios, pasture and cropland area decrease globally, which results in even more substantial yield increases needed to fulfil food demands (table 1). Throughout the afforestation scenarios, the highest rates of yield-increasing technological change are seen in 2020, when the





pricing policy on land-use emissions is implemented. These rates are, especially in the tropical regions, substantially higher than those observed in the recent past (Fischer *et al* 2014). Until the end of the century average annual technological change rates range between 0.44% in *BAU* and 1.34% in the *unrestricted* afforestation scenario. Large regional differences are observed, with yields being about 5.5 times as high in Africa at the end of the century in the *unrestricted* case compared to 2010, but less than double within Europe in the same scenario (see figure S8 for regional yield development).

Carbon sequestration

Afforestation leads to considerable carbon sequestration. While in the *BAU* case more than 90 Gt of CO_2 are released as a result of land-use change, up to 860 Gt CO_2 are sequestered in the case of *unrestricted* afforestation between 2010 and 2100. The pricing of CO_2 emissions from land-use change in the *avoided deforestation* scenario results in no net release of carbon from the land-use system.

Restricting afforestation to non-boreal and tropical regions reduces the area and therefore the amount of carbon sequestered (figure 2(a)). For the *no boreal* scenario carbon removal is 8%, and the afforested area about 13% lower globally compared to the *unrestricted* scenario. In the *only tropical* afforestation scenario, terrestrial carbon uptake is about 40% lower than in the *unrestricted* scenario, while afforestation area is reduced by about 50%. The stronger reduction of afforestation area relative to CDR is as a result of higher carbon accumulation rates in temperate and tropical forests compared to boreal regions.

Food price effects

The increasing food demand from a growing population with an increased per capita demand for meat products does not lead to very significant changes in food prices. In the *BAU* scenario, without any pricing of emissions from the land-use system, food prices are projected to stay rather constant, or to decrease slightly to about 10% lower than in 2010 (figure 2(b)), caused by a decline in demand towards the end of the century (figure S2). The exponentially increasing CO_2 price on land-use-changes emission in the *avoided deforestation* scenario prevents the conversion of pasture and forest to cropland. Increasing land scarcity and the necessary investment costs for research and development increase prices at maximum by about 40% on global average in this case.

Afforestation leads to competition for land between carbon sequestration and agricultural production and results in substantial food price increases. Under *unrestricted* afforestation food prices increase by about 80% up to 2050 and are on average more than four times higher in 2100 than in 2010. Excluding boreal regions from afforestation reduces this effect only by about 9% in 2100. However, when afforestation is limited to the zone of highest cooling effectiveness the tropics—the food price impact is significantly reduced. In the *only tropical* afforestation scenario, food prices peak in 2075 having increased by about 100%, followed by a decline in prices due to decreasing demand for food at times of high agricultural yields









and a slowdown of forest expansion. Especially in the *unrestricted* and *no boreal* scenarios, the additional land-use competition through afforestation influences prices much more strongly than the mere effect of emission pricing in the *avoided deforestation* scenario. Food prices are also sensitive to the CO_2 price. Lower CO_2 prices lead to lower carbon sequestration, but also reduce food prices (figure S9).

Food prices in different regions are affected differently by the modelled afforestation scenarios (figure 3). *Unrestricted* afforestation leads to the highest prices of all scenarios over the century within all regions, with the highest values occurring in Pacific Asia (PAS: 630) and Latin America (LAM: 640). In the Former Soviet Union (FSU) the increase is lowest, with prices three times higher in 2100.

Excluding the boreal zone from afforestation leads to lower food commodity prices than *unrestricted* afforestation, especially in regions that are partly in the boreal zone. In Europe (EUR) and FSU estimated food prices in 2100 are then about 30% lower. FSU turns into a net exporter of crops, EUR into a net exporter of livestock products towards the end of the century (figures S6 and S7), which also influences food prices in other regions. In Africa (AFR) and LAM, prices are 7% lower in the *no boreal* than in the *unrestricted* scenario in 2100, even though afforested area differs by less than 1% (see also figure 1).

Limiting afforestation to the tropical zone results in a food price index much closer to the BAU scenario, and much lower than for *unrestricted* and *no boreal* afforestation, but in tropical regions the price increases are still substantial. In Pacific Asia the food price index is highest in 2100 with a value of 400, while in Latin America the maximum index level of 219 is reached in 2070. The influence on temperate and boreal regions is much lower. In EUR, NAM and FSU the price indices are at maximum increased by 35% to





40% compared to the BAU case. In this scenario, food price increases are in all regions lower than the assumed increase in GDP (figure S5).

The effect of global trade under tropical afforestation

More liberalised trade helps to buffer food price increases driven by tropical afforestation. We compared the food prices of the only tropical scenario to a scenario where the deviation from historical trade patterns was twice as fast (figure 4). In this only tropical aff tradelib scenario the overall, interregional trade volume increases faster (see also figures S6 and S7). Latin America turns from an exporter of food commodities into a net importer towards the end of the century. Africa further increases its imports of livestock products, which are mostly supplied by North America. In 2075, the year in which prices are highest globally, food prices are reduced by more than 25% in Latin America and Africa (figure 4). In Pacific Asia, where food prices are highest in 2100, the price index changes from 400 to 219. Subsequent price increases in Europe are negligible. While trade liberalisation has a strong influence on prices, it does not decrease afforested area (1275 Mha) or the sequestered amount of carbon (552 Gt).

Discussion

Afforestation impacts food prices

Our results show that large-scale afforestation can lead to significant carbon sequestration in the land-use sector, but can also lead to strongly rising food prices. In our study, these food price increases were the consequence of a large-scale transformation of the land-use sector, where food has to be produced on a much smaller overall agricultural area. In the scenario of *unrestricted* afforestation, cropland area is reduced by almost half to a global value of about 800 Mha in 2100, and pasture shrinks by more than 50% to about 1465 Mha, values that were last observed at around the year 1900 (Klein Goldewijk *et al* 2011). This decline in agricultural areas is enabled by significant investments into yield-increasing technological change and comes along with a pronounced increase in food prices. Avoided deforestation alone does not drastically spike food prices, which is in line with an earlier study by Schneider et al (2011). The finding that afforestation drives up food prices is also the result of a previous study by Calvin et al (2014), in which afforestation was also incentivized by a price on emissions from landuse, and resulted in increasing wheat prices. In contrast to this study, we report a combined food price index for meat and food-crop products for different afforestation scenarios. We also compare food prices under afforestation to a scenario where emissions from land use are priced, which leads to avoided deforestation. This comparison shows that most of the price increase can in fact be attributed to afforestation, while the emissions pricing alone is of lesser importance.

Limiting afforestation to the tropics—where it is most effective in decreasing global temperatures -substantially reduces the impact on food prices. Earlier studies with earth system models showed that afforestation in the tropics, through the combined effect of carbon sequestration and albedo change, leads to a net cooling, while planting trees in the boreal zone might even increase global temperatures (Bala et al 2007, Bathiany et al 2010, Arora and Montenegro 2011). While this simplified, latitudinal dependence seems to hold true in general, exceptions are possible under specific site conditions. Since historical boreal and tropical deforestation took place on the most productive lands with above-average carbon stocks and belowaverage snow cover, a reforestation of some boreal areas might also decrease global temperatures (Pongratz et al 2011). And an afforestation of tropical and subtropical desert areas could result in net warming because of the prevalence of the albedo effect (Keller et al 2014). Desert areas with high albedo, however, were not considered for afforestation in our study. Rather, afforestation was restricted to agricultural areas in certain latitudinal zones, excluding boreal and temperate zones where afforestation might not show a global cooling effect. Integrating the albedo-induced radiative forcing effect of afforestation directly in the model, as has been done by Jones et al (2015), should be considered for future model applications.

While limiting afforestation to the tropics reduced food prices globally, food price indices remained higher in tropical regions. These increased price levels in the tropics could be buffered by a more liberalised trade policy, with an ensuing shift of agricultural production to non-tropical regions. However, this interregional reallocation would also increase the import dependency of some tropical regions and might hamper the development of the agricultural sector within these regions.

Afforestation requires the reversal of deforestation and R&D spending trends

Before afforestation can be considered as a serious means to mitigate climate change, deforestation has to come to an end. In our study this happened as soon as there was a price on CO₂ emissions from deforestation. At the moment, however, no such policy is in place on a global level and much of the carbon stored in tropical forests is released into the atmosphere. Gross carbon emissions from tropical regions were estimated to be around 0.81 GtC yr^{-1} between 2000 and 2005 (Harris et al 2012), with yearly emissions of deforestation from the Amazon basin alone accounting for 0.18 GtC between 2000 and 2010 (Song et al 2015). The current trend is opposite to what we described in our only tropical afforestation scenario. Between 1993 and 2012 tropical forests lost aboveground biomass carbon $(-0.21 \text{ GtC yr}^{-1})$, while boreal and temperate forests gained it by about the same amount $(+0.18 \text{ GtC yr}^{-1})$ (Liu et al 2015). However, Brazil-the country with the greatest absolute forest area reduction-has recently reduced its deforestation curve through conservation policies and stricter law enforcement on the ground (Assunção et al 2015, Tollefson 2015, FAO 2015b). China has initiated a large afforestation programme, with plans to increase afforested area by 40 Mha by 2020, a measure which was found not only to sequester carbon but also to decrease local land-surface temperatures (Peng et al 2014). And in December 2015, ten African countries launched AFR100, and initiative to restore 100 Mha of degraded and deforested land by 2030partly as a climate change mitigation measure (WRI 2015). These developments are just few of many that indicate that global afforestation efforts now have better prospects for success.

Continuous yield increases and substantial investment into yield-increasing R&D would be needed to fulfil the food demands of a growing population, especially when agriculture competes with afforestation. The high price on CO_2 emissions, and hence the strong incentive to free up agricultural land for afforestation, initiates continuous yield-increasing technological change in our study, with values well above those observed historically. In contrast to other partial equilibrium land-use models (e.g. GLOBIOM: Kraxner *et al* 2013, GCAM: Calvin *et al* 2014), technological



change is endogenously derived within MAgPIE (Dietrich et al 2014, Von Lampe et al 2014), and yields tend to increase stronger in response to additional pressures on the land-use system (Lotze-Campen et al 2014, Nelson et al 2014, Delincé et al 2015). During recent decades, yields of main staple crops increased linearly at average rates of 1% (wheat, rice, soybean) and 1.5% (maize), while the relative annual rate of increase constantly dropped (Fischer et al 2014). Increased investment into R&D would be needed to make afforestation a realistic option, but when research spending increased in recent years this was largely driven by the development in single countries like China and India. Almost every third OECD country actually had a negative trend in public agricultural R&D spending. And in the developing world, especially in Sub-Saharan Africa, where in our afforestation scenarios yields more than tripled between 2010 and 2100, public spending on agricultural R&D amounted to only about 1.6 billion US\$ or 5% of global agricultural R&D spending in 2008, and almost half the African countries had a negative trend in their budgets (Beintema et al 2012). This trend of low R&D spending would certainly have to turn around in order to achieve the yields projected in our model.

The yield increases triggered by afforestation could also alter agricultural N_2O and CH_4 emissions, a dynamic that was not in the focus of this study. Intensification could both increase or decrease N_2O emissions from soils, depending on whether intensification is reached through higher inputs (e.g. fertilizer) or better agronomic practices (Bodirsky and Müller 2014, Lassaletta *et al* 2014). CH₄ emissions from the livestock sector would likely be decreased by intensification due to a more efficient feed conversion (Herrero *et al* 2013).

Results set in context

The food-price increases presented in this study have to be seen in the context of a general increase in wealth. For this study we assumed the GDP development of the SSP2 scenario (Dellink et al 2015), which is steadily increasing for all model regions, and is also the basis for the increased per capita demand for food products. In most regions the rates of GDP increase are higher or in the same range as the price increases due to afforestation, so that share of expenditure for food would stay constant or decrease for a representative agent (see figure S5). Still, increases in wealth would not necessarily be distributed evenly among the population, so that the change in prices reported here could still have drastic impacts on the poorer parts of society. This is especially true for people whose share of expenditure on food is currently quite high, such as the poorest people in some African and Asian countries who currently expend above 70% of their available income on food (FAO 2015a).

A number of factors influence the formation of food prices, and our study focuses on the more longterm drivers. In the coming decades, a growing global population is expected to increase the demand for food, in particular for livestock products (Alexandratos and Bruinsma 2012, Bodirsky et al 2015). This, together with a likely elevated demand for bioenergy, will increase the total demand for agricultural products. These long-term trends are overlain by a number of more short-term factors affecting prices, such as weather variability, financial speculation or restrictive export policies in response to increasing prices (Mueller et al 2011). Lagi et al (2015), for instance, were able to replicate the FAO food price index between 2004 and 2012 with a dynamic model, where the underlying upward trend was due to an increasing demand for ethanol production, while the short-term peaks were caused by speculation. Our model is designed to capture the medium-term to long-term drivers of food price formation, and reveals the relative difference between afforestation scenarios and a world without forest-based climate mitigation. It does not consider specific policies and drivers on local or short time scale.

Food demand was provided exogenously to the model as a function of per capita income and population. Since price hikes in the afforestation scenarios were quite high with respect to the BAU case, it could be expected that the consumption of agricultural products declines, in spite of relatively low demand-toprice elasticises of food products, especially in high income countries (Hertel 2011, Muhammad et al 2011). Also for this reason, MAgPIE represented the upper range of food price estimates when climate change effects were assessed in a model intercomparison (Nelson et al 2014). However, we also assumed that currently developing regions become relatively wealthy towards the end of the century when food prices are projected to be at the highest level, which would result in lower shares of income expenditure on food and low demand elasticities.

Afforestation at the scale as described in this study would imply macro-economic effects that should be subject to further research, for instance within a general equilibrium framework. The MAgPIE model is a partial equilibrium model of the agricultural sector, impacts of afforestation on other sectors of the economy such as labour, capital and carbon markets were therefore not part of this study. We would expect that increasing food prices also increase the income of net food sellers, and reduce the incomes of net buyers as non-food expenditures are reduced, which could in consequence change the demand for food (Dorward 2012). Afforestation might also create new jobs in the short term for the planting of trees, but these jobs would vanish once the forests are established. Rent-seeking behaviour and opportunities to invest in land under a policy rewarding carbon removal could substantially shift production input factors from other



sectors. Furthermore, our analysis of trade was focused on the agricultural sector. For the *only tropical* afforestation scenario we assessed how trade liberalisation would influence regional food prices. We have, for instance, not considered how the consequential change in trade flows (e.g. increased imports of livestock products to Africa) would have to be compensated by trade flows in other sectors to avoid trade deficits, or how trade liberalisation would affect economies in general. Finally, the creation of an international market for carbon credits could create a substantial flow of money from CO_2 -emitting countries to those actively sequestering carbon through afforestation. These revenues could be used to finance, among other things, the import of food.

Conclusions

In order to mitigate climate change, land-based carbon dioxide removal will likely have to play an important role. Afforestation has been identified as a comparatively low-cost option to sequester carbon, but sideeffects of afforestation at large-scale were so far not much in the focus. Afforestation will, if it competes with food production for the same areas, lead to an increase in food prices. Moreover, as previous research has shown, afforestation in high latitudes will likely only have a small cooling effect on the global average temperature, or could even increase it, because of the counteracting albedo warming effect.

Our study confirms that afforestation offers a high potential for carbon dioxide removal, and more than 860 Gt of CO_2 are sequestered in our unrestricted afforestation scenario up to the end of the century. However, we also find that this afforestation leads to a more than fourfold increase in food prices by 2100. When afforestation is restricted to the tropics—and thus the albedo warming effect avoided—still substantial carbon sequestration can be achieved. This, at the same time, lowers global food prices substantially which nevertheless remain increased in tropical regions compared to a world without large-scale forest expansion. Our study suggests that a liberalisation of agricultural trade could further dampen the remaining price increases in tropical regions.

By sequestering carbon though afforestation, tropical regions would offer a valuable service for the benefit of the whole world. An international carbon market for carbon credits could be the source of monetary flows to those tropical countries undertaking afforestation and could compensate for some of the disadvantages coming along with it. Thoughtfully designed policies would have to avoid that established forests are cut down again and release the carbon stored. The raised money should also be used for investments into agricultural R&D, to achieve necessary rates of yield increase. And lastly, policies should be designed in a way which assures that not only land-



owner profit, but revenues are also distributed to those people affected most by the food price increases.

We conclude from our study that afforestation should not be seen as the silver bullet of climate change mitigation, but set in the right context and done at the right location it can well be a complement to other mitigation options.

Acknowledgments

The research was primarily funded by the Deutsche Forschungsgemeinschaft (DFG) under SPP ED 178/3-1 (CEMICS). In addition, the research leading to these results has received funding from the European Union's Seventh Framework Programme FP7 under grant agreement no. 603542 (LUC4C). The publication of this article was funded by the Open Access Fund of the Leibniz Association.

References

- Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision *ESA Working paper 12-03* (Rome: FAO) (www.fao.org/docrep/016/ap106e/ ap106e.pdf)
- Arora V K and Montenegro A 2011 Small temperature benefits provided by realistic afforestation efforts *Nat. Geosci.* **4** 514–8
- Assunção J, Gandour C and Rocha R 2015 Deforestation slowdown in the Brazilian Amazon: prices or policies? *Environ. Dev. Econ.* **20** 697–722
- Bala G, Caldeira K, Wickett M, Phillips T J, Lobell D B, Delire C and Mirin A 2007 Combined climate and carbon-cycle effects of large-scale deforestation *Proc. Natl Acad. Sci.* **104** 6550–5
- Bathiany S, Claussen M, Brovkin V, Raddatz T and Gayler V 2010 Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI earth system model *Biogeosciences* **7** 1383–99
- Beintema N, Stads G-J, Fuglie K and Heisey P 2012 *ASTI Global Assessment of Agricultural R&D Spending* (Washington, DC; Rome; Rome: International Food Policy Research Institute; Agricultural Science and Technology Indicators; Global Forum on Agricultural Research) (http://ifpri.org/sites/ default/files/publications/astiglobalassessment.pdf)
- Bodirsky B L and Müller C 2014 Robust relationship between yields and nitrogen inputs indicates three ways to reduce nitrogen pollution *Environ. Res. Lett.* **9** 111005
- Bodirsky B L, Rolinski S, Biewald A, Weindl I, Popp A and Lotze-Campen H 2015 Global food demand scenarios for the 21st century *PloS One* **10** e0139201
- Bonan G B 2008 Forests and climate change: forcings, feedbacks, and the climate benefits of forests *Science* **320** 1444–9
- Bondeau A *et al* 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob. Change Biol.* **13** 679–706
- Bonsch M *et al* 2016 Trade-offs between land and water requirements for large-scale bioenergy production *GCB Bioenergy* **8** 11–24
- Bright R M 2015 Metrics for biogeophysical climate forcings from land use and land cover changes and their inclusion in life cycle assessment: a critical review *Environ. Sci. Technol.* **49** 3291–303
- Bright R M, Zhao K, Jackson R B and Cherubini F 2015 Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities *Glob. Change Biol.* **21** 3246–66
- Calvin K, Clarke L, Krey V, Blanford G, Jiang K, Kainuma M, Kriegler E, Luderer G and Shukla P R 2012 The role of Asia in

mitigating climate change: results from the Asia modeling exercise *Energy Econ.* **34** S251–60

- Calvin K, Wise M, Kyle P, Patel P, Clarke L and Edmonds J 2014 Trade-offs of different land and bioenergy policies on the path to achieving climate targets *Clim. Change* 123 691–704
- Clarke L et al 2014 Assessing transformation pathways Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al (Cambridge: Cambridge University Press)
- Delincé J, Ciaian P and Witzke H 2015 Economic impacts of climate change on agriculture: the AgMIP approach J. Appl. Remote Sens. 9 097099
- Dellink R, Chateau J, Lanzi E and Magné B 2015 Long-term economic growth projections in the shared socioeconomic pathways *Glob. Environ. Change* in press (doi:10.1016/j. gloenvcha.2015.06.004)
- Dietrich J P, Popp A and Lotze-Campen H 2013 Reducing the loss of information and gaining accuracy with clustering methods in a global land-use model *Ecol. Modell.* **263** 233–43
- Dietrich J P, Schmitz C, Lotze-Campen H, Popp A and Müller C 2014 Forecasting technological change in agriculture—an endogenous implementation in a global land use model *Technol. Forecast. Soc. Change* **81** 236–49
- Dorward A 2012 The short- and medium- term impacts of rises in staple food prices *Food Secur.* 4 633–45
- Edmonds J, Luckow P, Calvin K, Wise M, Dooley J, Kyle P, Kim S H, Patel P and Clarke L 2013 Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy and CO₂ capture and storage? *Clim. Change* 118 29–43
- Erb K-H, Haberl H and Plutzar C 2012 Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability *Energy Policy* 47 260–9
- Erb K-H, Lauk C, Kastner T, Mayer A, Theurl M C and Haberl H 2016 Exploring the biophysical option space for feeding the world without deforestation *Nat. Commun.* 7 11382
- Fader M, Rost S, Müller C, Bondeau A and Gerten D 2010 Virtual water content of temperate cereals and maize: present and potential future patterns *J. Hydrol.* **384** 218–31
- FAO 2015a Food security indicators, share of food expenditure of the poor (bit.ly/14FRxGV)
- FAO 2015b Global Forest Resources Assessment 2015: How are the World's Forests Changing? Food and Agriculture Organization of the United Nations (http://fao.org/forestry/fra2005/en/)
- FAOSTAT 2010 Food and Agriculture Organization Corporate Statistical Database (http://faostat.fao.org/)
- Fischer T, Byerlee D and Edmeades G 2014 Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World? Australian Centre for International Agricultural Research (ACIAR)
- Fuss S et al 2014 Betting on negative emissions Nat. Clim. Change 4 850–3
- Harris N L, Brown S, Hagen S C, Saatchi S S, Petrova S, Salas W, Hansen M C, Potapov P V and Lotsch A 2012 Baseline map of carbon emissions from deforestation in tropical regions *Science* **336** 1573–6
- Herrero M, Havlík P, Valin H, Notenbaert A, Rufino M C, Thornton P K, Blümmel M, Weiss F, Grace D and Obersteiner M 2013 Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems *Proc. Natl Acad. Sci. USA* **110** 20888–93
- Hertel T W 2011 The global supply and demand for agricultural land in 2050: a perfect strom in the making? *Amer. J. Agr. Econ.* **93** 259–75
- Humpenöder F, Popp A, Dietrich J P, Klein D, Lotze-Campen H, Bonsch M, Bodirsky B L, Weindl I, Stevanovic M and Müller C 2014 Investigating afforestation and bioenergy CCS as climate change mitigation strategies *Environ. Res. Lett.* **9** 064029
- Humpenöder F *et al* 2015 Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation? *Environ. Sci. Technol.* **49** 6731–9



Jones A D, Calvin K V, Collins W D and Edmonds J 2015 Accounting for radiative forcing from albedo change in future global land-use scenarios *Clim. Change* **131** 691–703 KCS and Lutz W 2014 The human core of the shared

socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100 *Glob. Environ. Change* in press (doi:10.1016/j.gloenvcha.2014.06.004)

Keller D P, Feng E Y and Oschlies A 2014 Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario *Nat. Commun.* **5** 3304

Klein Goldewijk K, Beusen A, Van Drecht G and De Vos M 2011 The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12 000 years *Glob. Ecol. Biogeogr.* 20 73–86

Kraxner F *et al* 2013 Global bioenergy scenarios—future forest development, land-use implications, and trade-offs *Biomass Bioenergy* 57 86–96

Kriegler E, Edenhofer O, Reuster L, Luderer G and Klein D 2013 Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Clim. Change* **118** 45–57

Lagi M, Bar-Yam Y, Bertrand K Z and Bar-Yam Y 2015 Accurate market price formation model with both supply-demand and trend-following for global food prices providing policy recommendations *Proc. Natl Acad. Sci.* **11** 1–27

Lassaletta L, Billen G, Grizzetti B, Anglade J and Garnier J 2014 50 Year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland *Environ. Res. Lett.* **9** 105011

Liu Y Y, van Dijk A I J M, de Jeu R A M, Canadell J G, McCabe M F, Evans J P and Wang G 2015 Recent reversal in loss of global terrestrial biomass *Nat. Clim. Change* 5 470–4

Lotze-Campen H *et al* 2014 Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison *Agric. Econ.* **45** 103–16

Lotze-Campen H, Müller C, Bondeau A, Rost S, Popp A and Lucht W 2008 Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach *Agric. Econ.* **39** 325–38

Mueller S A, Anderson J E and Wallington T J 2011 Impact of biofuel production and other supply and demand factors on food price increases in 2008 *Biomass Bioenergy* **35** 1623–32

Muhammad A, Seale J L, Meade B and Regmi A 2011 International evidence on food consumption patterns: an update using 2005 international comparison program data USDA-ERS Technical Bulletin No. 1929 (doi:10.2139/ssrn.2114337)

Müller C and Robertson R D 2014 Projecting future crop productivity for global economic modeling *Agric. Econ.* **45** 37–50

Narayanan G B and Walmsley T L 2008 Global Trade, Assistance, and Production: The GTAP 7 Data Base (www.gtap.agecon. purdue.edu/databases/v7/)

Nelson G C *et al* 2014 Agriculture and climate change in global scenarios: why don't the models agree *Agric. Econ.* **45** 85–101

O'Neill B C *et al* 2015 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* in press (doi:10.1016/j. gloenvcha.2015.01.004)

Overmars K P, Stehfest E, Tabeau A, van Meijl H, Beltrán A M and Kram T 2014 Estimating the opportunity costs of reducing carbon dioxide emissions via avoided deforestation, using integrated assessment modelling *Land Use Policy* **41** 45–60

Peng S-S, Piao S, Zeng Z, Ciais P, Zhou L, Li L Z X, Myneni R B, Yin Y and Zeng H 2014 Afforestation in China cools local land surface temperature *Proc. Natl Acad. Sci.* **111** 2915–9

Persson U M 2015 The impact of biofuel demand on agricultural commodity prices: a systematic review *Wiley Interdiscip. Rev.* Energy Environ. 4 410–28

Pongratz J, Reick C H, Raddatz T, Caldeira K and Claussen M 2011 Past land use decisions have increased mitigation potential of reforestation *Geophys. Res. Lett.* **38** L15701 Popp A *et al* 2014 Land-use protection for climate change mitigation Nat. Clim. Change 4 2–5

Reilly J, Melillo J, Cai Y, Kicklighter D, Gurgel A, Paltsev S, Cronin T, Sokolov A and Schlosser A 2012 Using land to mitigate climate change: hitting the target, recognizing the trade-offs *Environ. Sci. Technol.* **46** 5672–9

Schmitz C 2012 The Future of Food Supply in a Constraining Environment, Modelling the Impact of Trade, Intensification, and Cropland Expansion on Agricultural and Environmental Systems (Humboldt University of Berlin) (http://edoc.huberlin.de/dissertationen/schmitz-christoph-2012-12-12/ PDF/schmitz.pdf)

Schmitz C, Biewald A, Lotze-Campen H, Popp A, Dietrich J P, Bodirsky B, Krause M and Weindl I 2012 Trading more food: Implications for land use, greenhouse gas emissions, and the food system *Glob. Environ. Change* **22** 189–209

Schneider U A *et al* 2011 Impacts of population growth, economic development, and technical change on global food production and consumption *Agric. Syst.* **104** 204–15

Siebert S, Döll P, Feick S, Frenken K and Hoogeveen J 2007 *Global Map of Irrigated Areas Version 4.0.1* (Germany/Rome, Italy: University of Frankfurt (Main)/ Food and Agriculture Organization of the United Nations)

- Smith P et al 2014 Agriculture, forestry and other land use (AFOLU) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed O Edenhofer et al (Cambridge: Cambridge University Press)
- Smith P et al 2015 Biophysical and economic limits to negative CO_2 emissions Nat. Clim. Change 6 42–50
- Song X-P, Huang C, Saatchi S S, Hansen M C and Townshend J R 2015 Annual carbon emissions from deforestation in the amazon basin between 2000 and 2010 *PloS One* **10** e0126754

Strengers B J, Van Minnen J G and Eickhout B 2008 The role of carbon plantations in mitigating climate change: potentials and costs *Clim. Change* 88 343–66

The World Bank 2015 Consumer price index (http://data. worldbank.org/indicator/FP.CPI.TOTL)

Tollefson J 2015 Stopping deforestation: battle for the Amazon Nature 520 20–3

UNFCCC 2015 FCCC/CP/2015/L.9/Rev.1 Adoption of the Paris Agreement (http://unfccc.int/resource/docs/2015/cop21/ eng/l09r01.pdf)

van Vuuren D P, van Vliet J and Stehfest E 2009 Future bio-energy potential under various natural constraints *Energy Policy* **37** 4220–30

Von Lampe M *et al* 2014 Why do global long-term scenarios for agriculture differ? An overview of the AgMIP global economic model intercomparison *Agric. Econ.* **45** 3–20

Waha K, van Bussel L G J, Müller C and Bondeau A 2012 Climatedriven simulation of global crop sowing dates *Glob. Ecol. Biogeogr.* 21 247–59

Weindl I, Lotze-Campen H, Popp A, Muller C, Havlik P, Herrero M, Schmitz C and Rolinski S 2015 Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture *Environ. Res. Lett.* **10** 94021

Weindl I, Lotze-Campen H, Popp A, Bodirski B and Rolinski S 2010 Impacts of livestock feeding technologies on greenhouse gas emissions Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security (http://ageconsearch. umn.edu/handle/91277)

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S J, Janetos A and Edmonds J 2009 Implications of limiting CO₂ concentrations for land use and energy *Science* **324** 1183–6

WRI 2015 African Countries Launch AFR100 to Restore 100 Million Hectares of Land (http://wri.org/news/2015/12/releaseafrican-countries-launch-afr100-restore-100-millionhectares-land)